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RESEARCH MEMORANDUM

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RESEARCH MEMORANDUM

COMPARISON OF VARIOUS HEAT EXCHANGERS FOR LIQUID-METAL NUCLEAR TURBOJET OVER RANGE OF FLIGHT AND OPERATING CONDITIONS

4537 By Robert G. Ragsdale

SUMMARY

A large number of liquid-metal-to-air heat-exchanger cores were analyzed for the nuclear-powered liquid-metal turbojet cycle to determine which types yield the best over-all net thrust per total engine weight. The calculations were carried out for a range of flight and engine operating conditions to establish the effects of these parameters on the relative merit of the heat exchangers. A shell-and-tube heat exchanger with air flowing through the tubes was taken as the standard of comparison in all cases.

The performances of all exchangers considered were initially evaluated at a median condition. Of the 15 core types investigated, four gave substantial improvement in engine performance over that of the shell-and-tube reference exchanger. The best exchanger of each of these four types and the shell-and-tube core were then investigated over a range of flight Mach numbers, altitudes, compressor pressure ratios, and core wall temperatures. For each condition, a relative specific thrust was obtained by dividing the net thrust per total engine weight for a given exchanger by that for the shell-and-tube exchanger at the same prescribed condition.

The advantage of a given heat exchanger over a shell-and-tube exchanger increases with increasing altitude and decreases with increasing flight Mach number, compressor pressure ratio, and core wall temperature. The best performance is given by heat exchangers with the air flowing through, rather than normal to, a passage of both primary and secondary surface. The use of stainless-clad copper fins with an effective thermal

conductivity of 108 compared with 16.3 for stainless-steel fins results in an increase of approximately 7 to 15 percent in net thrust per total engine weight for all exchangers evaluated.

INTRODUCTION

One of the proposed systems for the application of nuclear energy to aircraft propulsion is the liquid-metal turbojet cycle discussed in reference 1. In this cycle the thermal energy is delivered to the air by means of a heat exchanger rather than by fuel combustion. The heat is supplied to the exchanger by liquid metal heated in the reactor. The performance of the entire cycle depends to a large extent on the heat exchanger because of its weight and pressure-drop contributions. Reference 2 presents the performance characteristics of a considerable number of heat exchangers in a consistent manner.

The purpose of this study is to determine the relative merits of the available heat exchangers for the liquid-metal turbojet cycle. The criterion of engine performance is net thrust per total engine weight. Engine performance is affected by flight Mach number, altitude, compressor pressure ratio, and exchanger wall temperature. The evaluation of engine performance for many heat exchangers over a range of flight and operating conditions involves extensive calculations. The recent availability of an IBM 650 Magnetic Drum Data-Processing Machine has reduced the required computing time to a feasible level.

The results will indicate either (1) that the performance of the liquid-metal turbojet cycle is relatively independent of the heat-exchanger characteristics or (2) that certain geometry types yield a substantial improvement in engine performance. Whether extensive experimental testing is justified for certain core types can be determined from this type of information.

SYMBOLS

A	cross-sectional area, sq ft
c_p	specific heat, Btu/(lb)(°F)
D_{hy}	hydraulic diameter, $4(L_x A_{min}/S_x)$, ft
d_f	fin thickness, ft
F_n	net thrust, lb

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$\mathcal{F}_r$	relative specific thrust
f	friction factor
G_{max}	mass flow per unit minimum flow area, lb/(hr)(sq ft)
g	gravitational constant, 32.2 ft/(sec)(sec)
h	average air heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)
J	mechanical equivalent of heat, 778 (ft-lb)/Btu
j	heat-transfer parameter, $StPr^{2/3}$
k	thermal conductivity, Btu/(hr)(sq ft)($^{\circ}$F/ft)
L	length, ft
l_f	fin height, ft
M	Mach number
m	fin parameter, $\sqrt{2h/k_f d_f}$, 1/ft
P	absolute total pressure, lb/sq ft
Pr	Prandtl number, $c_p\mu/k$
p	absolute static pressure, lb/sq ft
q	rate of heat flow, or work, Btu/hr
R	gas constant, air, ft/$^{\circ}$R
Re	Reynolds number, $D_{hy}G_{max}/\mu$
S	surface area, sq ft
St	Stanton number, h/c_pG_{max}
T	absolute total temperature, $^{\circ}$R
t	absolute static temperature, $^{\circ}$R
V	velocity, ft/sec
W	weight, lb

w	weight-flow rate, lb/sec
z	altitude, ft
α	free flow area ratio, A_{min}/A_F
γ	ratio of specific heats for air, 1.4
δ	ratio of total pressure to NACA standard sea-level pressure of 2116 lb/sq ft
η	efficiency
θ	ratio of total temperature to NACA standard sea-level temperature of 519° R
μ	viscosity, lb/(hr)(ft)
ρ	density, lb/cu ft
σ	dimensionless grouping, $1 + \frac{\gamma - 1}{2} M^2$
$\Phi(\eta_x)$	heat-exchanger parameter, $\ln\left[1/(1 - \eta_x)\right]$
ψ	heat-transfer parameter, $(f/2)/\eta_o St$

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Subscripts:

av	average
b	bulk
C	compressor
E	engine less heat exchanger
EH	engine plus heat exchanger
F	frontal
f	film
f	fin
id	ideal
lm	log mean

max maximum

min minimum

o over-all surface

T turbine

w wall

4537 x exchanger

0 free stream; diffuser inlet

1 compressor inlet

2 compressor outlet

3 heat-exchanger inlet

4 heat-exchanger outlet

5 turbine inlet

6 turbine outlet

7 exhaust-nozzle outlet

METHOD OF ANALYSIS

Scope

In all, 46 heat-exchanger cores were initially considered; these represented 15 core types. The maximum net thrusts per engine weight for each of the cores were evaluated and compared at a given condition. This condition, a median of each of the flight and operating conditions considered, is as follows:

Flight Mach number, M_0 . . . . 2.0
Altitude, z, ft 60,000
Compressor total-pressure ratio, P_2/P_1 7
Core wall temperature, T_w, $^{\circ}R$ 2100

Of the fifteen core types, the best four at this condition and the reference core (a shell-and-tube heat exchanger) were selected for further investigation.

For a compressor pressure ratio of 7 and exchanger wall temperature of 2100° R, the flight Mach number and altitude were varied as follows: M_0 = 1.5, 2.0, and 2.5; z = 45,000, 60,000, and 80,000 feet. Each altitude was considered for each flight Mach number; that is, nine flight conditions.

For a flight Mach number of 2.0 and an altitude of 60,000 feet, the compressor pressure ratio and core wall temperature were varied as follows: P_2/P_1 = 3, 7, and 10; T_W = 1700°, 2100°, and 2400° R. Here 4537
all possible combinations were not considered; the compressor pressure ratio was varied for a wall temperature of 2100° R, and the wall temperature was varied for a compressor pressure ratio of 7.

For specified values of flight Mach number, altitude, compressor pressure ratio, and heat-exchanger core wall temperature, and for a given heat-exchanger type, there are two remaining degrees of freedom in engine performance. These are the heat-exchanger inlet-air velocity and the heat-exchanger length. These quantities are fixed if the inlet-air Mach number M_3 and outlet-air temperature T_4 are prescribed. These parameters must be considered as variables for a valid comparison of heat exchangers, since there is a best combination of M_3 and T_4 which yields a maximum net thrust per engine weight (ref. 1). These best values are a function of the heat-exchanger type. Heat-exchanger inlet-air Mach numbers investigated were 0.10, 0.15, 0.20, and 0.25. For each assigned value of M_3, the core outlet-air temperature was varied over a range of temperatures which approached the assigned wall temperature. The values of T_4 taken for each wall temperature were as follows:

T_4, °R					T_W, °R
1450	1550	1625	1650	1675	1700
1800	1900	1950	2000	2050	2100
2100	2200	2250	2300	2350	2400

For prescribed flight Mach number, altitude, compressor pressure ratio, and wall temperature, 20 cycle calculations are required to obtain the best combination of M_3 and T_4 for each heat exchanger.

Assumptions

In the basic cycle calculation, the following assumptions are made:

(1) The airflow through the inlet diffuser is adiabatic.

(2) The compression process is polytropic.

(3) The polytropic efficiency of compression is 0.88.

(4) The airflow through the heat-exchanger inlet and outlet ducting is adiabatic, and the total-pressure ratio across each is 0.95.

(5) The perfect gas law is valid.

(6) The ratio of specific heats γ for air is 1.4.

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(7) The heat exchanger operates at constant wall temperature.

(8) The heat exchanger is stainless steel.

(9) The turbine adiabatic efficiency is 0.90.

(10) The flow through the jet nozzle is an isentropic process, with a velocity coefficient of 0.97.

(11) The engine weight per pound of standard sea-level airflow is $20\sqrt{\theta}/\delta$, lb/(lb/sec).

(12) The airflow per unit compressor frontal area is $30\ \delta/\sqrt{\theta}$, (lb/sec)/sq ft.

Basic Cycle Relations

The basic cycle calculation involves a stepwise computation through the engine. Figure 1 illustrates the stations considered. The end point of the calculation is the net thrust per total engine weight, as given by

$$\frac{F_n}{W_{EH}} = \frac{\dfrac{F_n}{w}}{\dfrac{W_X}{w} + \dfrac{W_E}{w}} \tag{1}$$

The weight of the engine less heat exchanger W_E per pound of air is obtained from the following relation (assumption (11)):

$$\frac{W_E}{w} = \frac{20\sqrt{\theta}}{\delta}, \text{ lb/(lb/sec)} \tag{2}$$

Equation (2) has been determined from the weights and airflows of existing turbojet engines. The actual magnitude of this weight is of less importance than the fact that it is held constant while only the heat exchanger is varied.

The evaluation of the heat-exchanger weight per pound of air W_x/w is indicated in the following section.

The net thrust per pound of air is obtained from

$$\frac{F_n}{w} = \frac{(V_7 - V_0)}{g} \tag{3}$$

The free-stream velocity V_0 is given by

$$V_0 = M_0\sqrt{\gamma g R t_0} \tag{4}$$

For prescribed flight Mach number and altitude, reference 3 gives values of t_0, p_0, t_0/T_0, and p_0/P_0 (see table I). For an isentropic expansion, with the velocity coefficient taken as 0.97, the exhaust velocity V_7 is found as indicated in reference 4:

$$V_7 = 0.97\sqrt{2gJc_{p,6}T_6}\left[1 - \left(\frac{p_0}{P_6}\right)^{\frac{\gamma-1}{\gamma}}\right]^{1/2} \tag{5}$$

The pressure ratio p_0/P_6 is obtained from the following expression:

$$\frac{P_6}{p_0} = \frac{P_0}{p_0}\frac{P_1}{P_0}\frac{P_2}{P_1}\frac{P_3}{P_2}\frac{P_4}{P_3}\frac{P_5}{P_4}\frac{P_6}{P_5} \tag{6}$$

The turbine discharge temperature is given by

$$T_6 = t_0\frac{T_0}{t_0}\frac{T_1}{T_0}\frac{T_2}{T_1}\frac{T_3}{T_2}\frac{T_4}{T_3}\frac{T_5}{T_4}\frac{T_6}{T_5} \tag{7}$$

The pressure ratios in equation (6) are obtained individually. The ratio p_0/P_0 is given in reference 3 as a function of flight Mach number. The diffuser pressure recovery P_1/P_0 is plotted as a function of flight Mach number in reference 1. The values of P_1/P_0 which were used are listed in table I. The compressor pressure ratio P_2/P_1 is an assigned parameter. The pressure ratios across the heat-exchanger ducting, P_3/P_2 and P_5/P_4, are taken as 0.95 (assumption (4)). The pressure ratio P_4/P_3 is obtained from the heat-exchanger calculations and will be treated in the following section. The final pressure ratio P_6/P_5 is given by

$$\frac{P_6}{P_5} = \left(\frac{T_{6,id}}{T_5}\right)^{\frac{\gamma}{\gamma-1}} \tag{8}$$

[redacted]

where $T_{6,id}/T_5$ is from the turbine calculations, which also yield the temperature ratio T_6/T_5 in equation (7).

The temperature ratios in equation (7) are obtained in the following manner. The ratio t_0/T_0 and t_0 are given in reference 3 for specified flight Mach number and altitude (see table I). The diffuser temperature ratio T_1/T_0 is unity by assumption (1). The compressor temperature ratio is given by

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$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma\eta_C}} \tag{9}$$

where η_C is 0.88 (assumption (3)). By virtue of assumption (4), the ratios T_3/T_2 and T_5/T_4 are unity. The temperature ratio T_4/T_3 is obtained from the heat-exchanger calculations. The turbine temperature ratio is obtained from the relation

$$\frac{T_6}{T_5} = \frac{c_{p,5} - \left[\dfrac{c_{p,2} - c_{p,1}\left(\dfrac{T_1}{T_2}\right)}{\dfrac{T_4}{T_3}}\right]}{c_{p,6}} \tag{10}$$

The ideal temperature ratio, necessary for P_6/P_5 in equation (8), is given by

$$\frac{T_{6,id}}{T_5} = \frac{c_{p,5} - \dfrac{1}{\eta_T}\left[\dfrac{c_{p,2} - c_{p,1}\left(\dfrac{T_1}{T_2}\right)}{\dfrac{T_4}{T_3}}\right]}{c_{p,6}} \tag{11}$$

where η_T is taken to be 0.90 (assumption (9)).

These equations, (1) to (11), give the necessary relations for the calculation of engine performance, as measured by net thrust per total engine weight. Two given heat exchangers may be compared by evaluating $(F_n/W_{EH})_{max}$ for each. The ratio of the two $(F_n/W_{EH})_{max}$ values, or relative specific thrust, is a measure of the improvement in engine performance due to a variation of heat exchangers. Thus, many heat exchangers may be comparatively evaluated by selecting a reference heat exchanger and then computing the relative specific thrust of each with respect to it.

Heat-Exchanger Relations

For a given heat exchanger, expressions must be developed which will yield values for the quantities A_3/w, T_4/T_3, P_4/P_3, and W_x/w. If the Mach number of the heat-exchanger inlet air is assigned, the air inlet static temperature is given by 4537

$$t_3 = \frac{T_3}{\sigma_3} \tag{12}$$

where

$$\sigma_3 = 1 + \frac{\gamma - 1}{2} M_3^2$$

and the total temperature T_3 is given by the first five terms of equation (7):

$$T_3 = t_0 \frac{T_0}{t_0} \frac{T_1}{T_0} \frac{T_2}{T_1} \frac{T_3}{T_2} \tag{13}$$

In a similar manner,

$$p_3 = \frac{P_3}{(\sigma_3)^{\frac{\gamma}{\gamma-1}}} \tag{14}$$

where

$$P_3 = p_0 \frac{P_0}{p_0} \frac{P_1}{P_0} \frac{P_2}{P_1} \frac{P_3}{P_2} \tag{15}$$

The inlet-air density is obtained from the perfect gas law:

$$\rho_3 = \frac{p_3}{Rt_3} \tag{16}$$

The inlet velocity is then given by

$$V_3 = M_3\sqrt{\gamma g R t_3} \tag{17}$$

The exchanger flow area per pound of air flowing per second is

$$\frac{A_3}{\text{[redacted]}} = \frac{1}{V_3\rho_3} \tag{18}$$

[redacted]

For an assigned value of the exchanger exit air temperature, the required heat release is given by

$$\frac{q_x}{w} = c_{p,4}T_4 - c_{p,3}T_3 \qquad (19)$$

If the wall temperature of the exchanger T_w is now specified, there are no remaining degrees of freedom, and the required length of the core may be determined. The pressure ratio across the exchanger
4537 P_4/P_3 may also be computed. From the assigned value of T_w, the air film temperature is:

$$T_f = \frac{1}{2}(T_b + T_w)$$

where the air bulk temperature is

$$T_b = \frac{1}{2}(T_3 + T_4)$$

The physical properties can be evaluated from

$$\left.\begin{aligned} c_{p,f} &= \varphi_1(T_f) \\ \mu_f &= \varphi_2(T_f) \\ k_f &= \varphi_3(T_f) \\ Pr_f &= \varphi_1(\varphi_2/\varphi_3) \end{aligned}\right\} \qquad (20)$$

where

$$\varphi_i = A_i + B_i T_f + C_i T_f^2 + \ldots + H_i T_f^7$$

The numerical values of the constants $A_i, \ldots, H_i$ are presented in table II. These φ functions represent physical properties taken from reference 5 for temperatures from 500° to 1800° R.

For a selected heat exchanger the hydraulic diameter D_{hy} is known, and the Reynolds number is

$$Re_f = \frac{D_{hy}G_{max}}{\mu_f} \qquad (21)$$

where

$$G_{max} = \frac{1}{A_3/w}$$

[redacted]

If the heat-transfer factor is a known function of Reynolds number, then

$$j = A_j + B_j (Re_f)^{C_j} \tag{22}$$

These constants were evaluated for all heat exchangers considered (see HEAT-EXCHANGER DESCRIPTION PARAMETERS) and are tabulated in table III.

By definition,

$$j = StPr^{2/3} = \left(\frac{h}{c_{p,f} G_{max}}\right) Pr_f^{2/3} \tag{23}$$

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From equation (23), the heat-transfer coefficient is

$$h = \frac{c_{p,f} G_{max} j}{Pr_f^{2/3}} \tag{24}$$

If the exchanger is of an extended-surface type, the effectiveness of an untapered straight fin (ref. 6) is

$$\eta_f = \frac{\tanh m l_f}{m l_f} \tag{25}$$

where

$$m = \sqrt{2h/k_f d_f}$$

The over-all surface effectiveness is then given by

$$\eta_o = 1 - \left(\frac{S_f}{S_x}\right)(1 - \eta_f) \tag{26}$$

The temperature driving force at the core inlet is

$$\Delta T_3 = T_w - T_3 \tag{27}$$

and at the outlet,

$$\Delta T_4 = T_w - T_4 \tag{28}$$

The log mean temperature difference is

$$\Delta T_{lm} = \frac{\Delta T_3 - \Delta T_4}{\ln(\Delta T_3/\Delta T_4)} \tag{29}$$

For a constant wall temperature and ΔT_{lm} as given by equation (29), the required heat-exchanger surface is

$$\frac{S_x}{w} = \frac{\frac{q_x}{w}}{\eta_o h \Delta T_{lm}} \tag{30}$$

For a given exchanger the quantity S_x/L_xA_3 (see HEAT-EXCHANGER DESCRIPTION PARAMETERS and table III) is known, and the exchanger length is
4537 given by

$$L_x = \frac{\frac{S_x}{w}}{\left(\frac{A_3}{w}\right)\left(\frac{S_x}{L_xA_3}\right)} \tag{31}$$

The static-pressure drop through the exchanger core is given by (ref. 7):

$$(p_3 - p_4) = \left[\frac{4\left(\frac{L_x}{D_{hy}}\right)\left(\frac{f}{2}\right)G_{max}^2}{g\rho_{av}}\right] + \frac{G_{max}^2}{g}\left(\frac{1}{\rho_4} - \frac{1}{\rho_3}\right) \tag{32}$$

Equation (32) may be written in terms of the parameters of direct interest through a consideration of certain heat-transfer relations. A heat balance on the airstream gives

$$wc_{p,b}(T_4 - T_3) = h\eta_o S_x \Delta T_{lm} \tag{33}$$

By definition,

$$D_{hy} = 4\left(\frac{L_xA_3}{S_x}\right) \tag{34}$$

Substituting (34) into (33) gives

$$wc_{p,b}(T_4 - T_3) = 4(L_x/D_{hy})(h\eta_o A_3)(\Delta T_{lm}) \tag{35}$$

Combining equations (35) and (29), considering $c_{p,b} = c_{p,f}$, and rearranging terms give

$$4(L_x/D_{hy})\eta_o St_f = \ln\left(\frac{1}{1 - \eta_x}\right) \tag{36}$$

where

$$\eta_x = \frac{T_4 - T_3}{T_w - T_3}$$

Equation (36) may be written in the form

$$4(L_x/D_{hy})(f/2) = \psi\ \Phi(\eta_x) \tag{37}$$

where the two functions ψ and $\Phi(\eta_x)$ are defined by

$$\left.\begin{aligned} \psi &= (f/2)/\eta_o St_f \\ \Phi(\eta_x) &= \ln\left[1/(1 - \eta_x)\right] \end{aligned}\right\} \tag{38}$$

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Now, combining equations (37) and (32) yields

$$(p_3 - p_4) = \frac{\psi\,\Phi(\eta_x)G_{max}^2}{g\rho_{av}} + \frac{G_{max}^2}{g}\left(\frac{1}{\rho_4} - \frac{1}{\rho_3}\right) \tag{39}$$

By definition,

$$M_3^2 = \frac{V_3^2}{\gamma g p_3/\rho_3} = \frac{RG_{max}^2 t_3}{\gamma g p_3^2} \tag{40}$$

The approximation that $T_{av} = t_{av}$ gives the average density as

$$\rho_{av} = \frac{1}{R}\left(\frac{p_{av}}{T_{av}}\right) = \frac{1}{R}\left(\frac{p_3 + p_4}{T_3 + T_4}\right) \tag{41}$$

If equations (40) and (41) are substituted into equation (39), and $1/\rho$ is evaluated as (RT/p), the static-pressure ratio across the heat exchanger is

$$\frac{p_4}{p_3} = \sqrt{1 - \frac{\gamma M_3^2}{t_3}\left[\psi\ \Phi(\eta_x)(T_4 + T_3) + (T_4 - T_3) + \frac{T_4}{p_4/p_3} - T_3\left(\frac{p_4}{p_3}\right)\right]} \tag{42}$$

This expression is implicit in p_4/p_3 and requires an iteration procedure. The following expression provides an approximation of p_4/p_3 to be used as a starting value in equation (42):

$$\frac{p_4}{p_3} = \sqrt{1 - \frac{\gamma M_3^2}{t_3}(2T_w)\left[\psi\ \Phi(\eta_x) + \eta_x(1 - \psi)\left(1 - \frac{t_3}{T_w}\right)\right]} \tag{43}$$

Equation (43), which assumes that the quantity $(1 - \gamma M^2)$ is unity throughout the exchanger, yields values of p_4/p_3 that are greater than those given by equation (42).

The outlet static pressure is given by

$$p_4 = p_3\left(\frac{p_4}{p_3}\right)$$

where p_3 is known from equation (14).

As shown by equation (4) of reference 8, the static temperature at
4537 the exchanger exit can be obtained from

$$t_4 = \beta_4\left[\sqrt{1 + 2(T_4/\beta_4)} - 1\right] \tag{44}$$

where

$$\beta_4 = \left[\frac{\gamma g p_4^2}{(\gamma - 1)RG_{max}^2}\right]$$

The remaining heat-exchanger exit quantities are determined as follows:

$$\left.\begin{aligned}
\rho_4 &= \frac{p_4}{Rt_4} \\
V_4 &= \frac{G_{max}}{\rho_4} \\
M_4 &= V_4/\sqrt{\gamma g R t_4} \\
\sigma_4 &= 1 + \left(\frac{\gamma - 1}{2}\right)M_4^2 \\
P_4 &= p_4(\sigma)^{\frac{\gamma}{\gamma-1}}
\end{aligned}\right\} \tag{45}$$

The total-pressure ratio across the exchanger P_4/P_3 is found from equations (15) and (45). The temperature ratio T_4/T_3 is given by equation (13) and the assigned value of T_4. The quantity A_3/w is given by equation (18). The heat-exchanger weight per pound of airflow is given by

$$\frac{W_x}{w} = L_x\left(\frac{A_3}{w}\right)\left(\frac{W_x}{L_x A_3}\right) \tag{46}$$

[redacted]

where L_x is from equation (31), and W_x/L_xA_3 is known for a given exchanger (see HEAT-EXCHANGER DESCRIPTION PARAMETERS and table III).

Ratio of Heat-Exchanger to Compressor Area

The relations presented in the two preceding sections are sufficient
to evaluate the engine performance at specified flight and operating con-
ditions for a given exchanger. Another consideration as to the feasi-
bility of a heat exchanger is that the frontal area of the heat exchanger 4537
must not greatly exceed that of the compressor. Thus, the ratio of heat-
exchanger frontal area to compressor area is a parameter of interest.

This ratio may be evaluated from

$$\frac{A_F}{A_C} = \frac{A_F}{A_3}\frac{A_3}{w}\frac{w}{A_C} \tag{47}$$

The ratio A_F/A_3 is simply $1/\alpha$, where α is the free-flow factor of the heat exchanger. The ratio A_3/w is given by equation (18). The ratio of airflow rate to compressor area may be obtained from assumption (12):

$$(w/A_C)(\sqrt{\theta}/\delta) = 30(\text{lb/sec})/\text{sq ft} \tag{48}$$

By combining equations (47), (48), (9), (12), (14), (16), (17), and (18), the following expression may be obtained:

$$\left(\frac{A_F}{A_C}\right) = \frac{\left(30\,\frac{\sqrt{519}}{2116}\right)\left(\frac{R}{\gamma g}\right)^{1/2}(\sigma)^3}{\alpha M_3\left(\frac{P_3}{P_2}\right)\left(\frac{P_2}{P_1}\right)^{1-\frac{\gamma-1}{2\gamma\eta_C}}} \tag{49}$$

Equation (49) indicates the direct dependence of the area ratio on M_3 and compressor pressure ratio. Although M_3 is necessarily optimized with respect to engine performance, a value somewhat greater than optimum may be suggested by equation (49) if the exchanger frontal area exceeds that of the compressor.

HEAT-EXCHANGER DESCRIPTION PARAMETERS

A heat exchanger may be described by certain parameters. These parameters have been divided into those which describe the physical characteristics, and those which describe the heat-transfer and friction-loss performance characteristics. The numerical values of these parameters are tabulated in table III.

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Fifteen core types were investigated. A consideration of various core dimensions of a given type resulted in a total of 46 cores that were studied. The 15 core types fall into four basic classes:

Class	Type of flow	Heat exchanger
I	Flow through a passage of primary heating surface	1,2,3
II	Flow normal to primary heating surface	4,5,6,7
III	Flow through a passage of primary and secondary heating surface	8,9,10,11
IV	Flow normal to primary and secondary heating surface	12,13,14,15

Table III lists the descriptive titles of the cores considered; pictorial representations and dimensions of all exchangers are presented in reference 2 in the figures indicated in table III.

Physical Parameters

The hydraulic diameter, fin thickness, fin height, and the ratio of fin surface to total surface area are given in reference 2 (see table III). The total heat-transfer surface per unit length per unit minimum flow area S_x/L_xA_3 is obtained from the definition of hydraulic diameter as given by equation (34).

A necessary parameter not given in reference 2 is W_x/L_xA_3, the exchanger weight per unit length per unit minimum flow area. This quantity was obtained by calculating the weight of an exchanger with a 1-square-foot frontal area and a 1-foot length. The metal density was taken to be 0.29 pound per cubic inch. For all exchangers the thickness of walls forming flow passages was taken to be 0.016 inch. The shell or outer wall of the unit exchanger was assigned a thickness of 0.125 inch.

Performance Parameters

The heat-transfer parameter j and the friction factor f are tabulated and plotted against Reynolds number Re in reference 2. For each exchanger considered, a function of the form $A + BRe^C$ was evaluated for j and for f. When the curves of reference 2, presented on logarithmic coordinates, were straight lines, the constant A was taken as zero and the form BRe^C was used. For constant f or j with respect to Reynolds number, the constant B was taken as zero and A as the constant value. The constants A, B, and C once obtained were then used to check j and f values at Reynolds numbers other than those used to evaluate the constants to ensure that the curves were adequately described.

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The heat-transfer and friction characteristics of core 1 as presented in reference 2 were best represented by the constants given in table III. The net thrust per engine weight evaluated by using the conventional constants of $B_j = 0.023$ and $B_f = 0.046$ (ref. 8) differed by less than 2 percent from that obtained with the constants of table III.

The constants A, B, and C were evaluated to represent the curves of reference 2 in the turbulent region. These constants were then used to extrapolate the curves farther into the turbulent range. It was felt that, had the constants been evaluated to represent both the turbulent and laminar regions as one equation, the extrapolation of such a curve would be less reliable. Figure 2 shows a comparison of a typical curve from reference 2 and the equation used to represent it.

RESULTS AND DISCUSSION

For each of the 46 heat-exchanger cores the maximum net thrust per total engine weight was evaluated for the following conditions: $M_0 = 2.0$, $z = 60{,}000$ feet, $P_2/P_1 = 7$, and $T_w = 2100^\circ$ R. With the restriction that each be of a different type, the best four exchangers for these conditions are 8-1, 9-9, 10-2, and 11 (see table IV). Figure 3 gives schematic representations of core types 8, 9, 10, and 11. These four cores and the shell-and-tube reference core were evaluated at various flight Mach numbers, altitudes, compressor pressure ratios, and wall temperatures. For each of these four core configurations, a maximum F_n/W_{EH} was evaluated for selected values of M_0, z, P_2/P_1, and T_w. A relative specific thrust was obtained by dividing the $(F_n/W_{EH})_{max}$ by that of the shell-and-tube exchanger for the same conditions.

Figure 4 shows the effect of flight Mach number on relative specific thrust for three altitudes. The exchanger cores shown here and in

[redacted]

figures 5 to 9 are those noted as the four best. Figure 4 is for a wall temperature of 2100° R and a compressor pressure ratio of 7. The curves of figure 4 indicate the following:

(1) The advantage of these exchangers over the shell-and-tube core diminishes with increasing flight Mach number.

(2) At higher altitudes, the relative specific thrust is less sensitive to changes of flight Mach number.

(3) Core 9-9, the louvered-plate fin type, is the best exchanger for this range of flight conditions.

Figure 5, a cross plot of figure 4, shows the effect of altitude on relative specific thrust for three flight Mach numbers. From these curves it may be concluded that:

(1) The advantage of these extended-surface cores over a shell-and-tube core increases with altitude.

(2) The variation of relative specific thrust with altitude is not greatly affected by flight Mach number.

Figures 6 and 7 show the effects of compressor pressure ratio and exchanger wall temperature on relative specific thrust. These curves are for a flight Mach number of 2.0 and an altitude of 60,000 feet. The effects indicated are:

(1) The relative specific thrust decreases with increasing P_2/P_1 or T_W.

(2) As either P_2/P_1 or T_W is further increased, the performance of these cores approaches that of a shell-and-tube exchanger.

(3) Core 9-9 is again the best core for the range of conditions shown.

In general, the advantage of the exchangers shown over a shell-and-tube exchanger increases with increasing altitude, and decreases with increasing flight Mach number, compressor pressure ratio, and exchanger wall temperature. At the favorable condition of low flight Mach number and high altitude, an increase in engine performance of approximately 25 percent is possible. At a more favorable compressor pressure ratio of 3, an increase of 30 percent may be realized. At high flight Mach numbers and low altitudes, the possible gain is 10 percent.

The results of the cores investigated indicate certain favorable heat-exchanger characteristics. For the range of conditions studied, the best type of liquid-metal nuclear turbojet heat exchanger would appear to have the following geometrical features:

(1) Passages composed of both primary and secondary heat-transfer surface

(2) Airflow parallel rather than normal to passage elements

(3) Passages that disturb boundary-layer buildup.

Heat exchangers 1 to 7 have only primary surface. Exchangers 12 to 15 have secondary surface but the airflow is normal to the primary surfaces. The four best exchangers (8-1, 9-9, 10-2, and 11) are the only ones with extended surface in which the airflow is parallel to the passage elements. The plain-plate fin exchanger (core 8-1) lacks the characteristic of boundary-layer disturbance, and figures 4 to 7 indicate that it gives the lowest over-all performance of the four best cores. The louvered-plate fin exchanger (core 9-9), has the best over-all performance and is the core with the greatest boundary-layer disturbance. 4537

Figures 4 to 7 show the performance of the four best cores with extended surfaces of stainless steel ($k_f = 16.3$). Maximum net thrusts per total engine weight are shown in table IV for several of the extended-surface exchangers using a fin thermal conductivity of 108. This corresponds to stainless-steel-clad copper fins. Again with the restriction that each be of a different type, exchangers 8-1, 9-9, 10-2, and 11 are the best four cores. Exchanger 14-2, a plate-fin flat-tube core, has essentially the same performance as core 8-1.

The effect of fin thermal conductivity on relative specific thrust for exchanger cores 8-1, 9-9, 10-2, 11, and 14-2 is shown in figure 8. The increase of thermal conductivity yields an increase in performance because of the increased fin effectiveness. As the fin effectiveness approaches a value near 1.0, a further increase of fin conductivity has little effect on performance. The increased thermal conductivity results in a performance increase of 7 to 15 percent.

The effects of altitude and flight Mach number on the relative specific thrust of these five cores are shown in figure 9 for a fin thermal conductivity of 108. These curves, which are for a wall temperature of 2100° R and a compressor pressure ratio of 7, show the same effects as were indicated by figures 4 and 5, which were for a fin conductivity of 16.3; that is, relative specific thrust increases with altitude and decreases with flight Mach number. It is of interest that exchanger 14-2, the plate-fin flat-tube exchanger, gives an increase in performance from 19 to 25 percent over that of a shell-and-tube exchanger. Although this exchanger gives a lower performance than exchangers 9-9, 10-2, and 11 for the same fin material, it has an important advantage of feasibility of fabrication.

As pointed out in METHODS OF ANALYSIS, the ratio of core frontal area to compressor area must be considered. Nearly all of the cores studied were acceptable with respect to size. For a typical set of numbers ($\alpha = 0.4$, $M_3 = 0.15$, $P_2/P_1 = 7$), equation (49) gives a value of (A_F/A_C) of 1.22. This value is satisfactory. A rigorous study of this parameter involves certain engine design considerations and is beyond the scope of this report.

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SUMMARY OF RESULTS

For flight Mach numbers from 1.5 to 2.5, altitudes from 45,000 to 80,000 feet, compressor pressure ratios from 3 to 10, and heat-exchanger wall temperatures from 1700° to 2400° R, the maximum net thrust per total engine weight of a nuclear liquid-metal turbojet engine was evaluated for four heat-exchanger core types. These cores were selected from an initial evaluation of 46 exchangers representing 15 core types. The performance of the best of each of the four types was compared with that of a shell-and-tube exchanger with the air flowing through the tubes, operating at the same conditions. The effect of increased fin thermal conductivity comparable to stainless-steel-clad copper fins was evaluated. The following results were obtained:

1. A heat exchanger for a nuclear liquid-metal turbojet application within the range of conditions investigated should have the following characteristics: (a) passages composed of both primary and secondary heat-transfer surface, (b) airflow parallel rather than normal to passage elements, and (c) passages that disturb boundary layer buildup.

2. The advantage of a given exchanger over a shell-and-tube core increases with increasing altitude and decreases with increasing flight Mach numbers, compressor pressure ratio, and exchanger wall temperature.

3. The maximum possible increase in net thrust per total engine weight occurs at low flight Mach numbers and high altitudes and is approximately 30 percent for the exchangers and range of conditions investigated.

4. The use of stainless-clad copper fins with an effective thermal conductivity of 108 compared with 16.3 for stainless-steel fins results in an increase of approximately 7 to 15 percent in net thrust per total engine weight for all exchangers evaluated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 20, 1957

REFERENCES

1. Wachtl, William W., and Rom, Frank E.: Analysis of the Liquid-Metal Turbojet Cycle for Propulsion of Nuclear Powered Aircraft. NACA RM E51D30, 1951.

2. Kays, W. M., and London, A. L.: Compact Heat Exchangers. The National Press, Palo Alto (Calif.), 1955.

3. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rep. 1135, 1953. (Supersedes NACA TN 1428.) 4537

4. Faires, Virgil Moring: Elementary Thermodynamics. The MacMillan Co., 1941.

5. Hilsenrath, Joseph, et al.: Tables of Thermal Properties of Gases. Circular No. 564, NBS, 1955.

6. Gardner, Karl A.: Efficiency of Extended Surface. Trans. ASME, vol. 67, no. 8, Nov. 1945, pp. 621-631.

7. McAdams, W. H.: Heat Transmission. Third ed., McGraw-Hill Book Co., Inc., 1954.

8. Humble, Leroy V., Lowdermilk, Warren H., and Desmon, Leland G.: Measurements of Average Heat-Transfer and Friction Coefficients for Subsonic Flow of Air in Smooth Tubes at High Surface and Fluid Temperatures. NACA Rep. 1020, 1951. (Supersedes NACA RM's E7L31, E8L03, E50E23, and E50H23.)

9. Sams, E. W.: Heat Transfer and Pressure Drop Characteristics of Wire-Coil-Type Turbulence Promoters. Paper No. 15, Reactor Heat Transfer Conf. (New York City), Nov. 1, 1956.

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TABLE I. - FLIGHT-CONDITION PARAMETERS

[Free-stream static temperature, t_0, 392.4° R.[a]]

Flight Mach number, M_0	Altitude, z, ft	p_0, lb/sq ft (a)	t_0/T_0 (a)	p_0/P_0 (a)	P_1/P_0 (b)
1.5	45,000	308.0	0.6897	0.2724	0.950
	60,000	150.9	↓	↓	↓
	80,000	58.0			
2.0	45,000	308.0	0.5556	0.1278	0.925
	60,000	150.9	↓	↓	↓
	80,000	58.0			
2.5	45,000	308.0	0.4444	0.0585	0.825
	60,000	150.9	↓	↓	↓
	80,000	58.0			

[a]Ref. 3. [b]Ref. 1.

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TABLE II. - PHYSICAL PROPERTIES

[The physical properties of air, as given in ref. 5, have been evaluated as functions of temperature in the form: $A_i + B_iT + C_iT^2 + \ldots + H_iT^7$, $T = {}^{\circ}R$.]

	c_p, Btu/(lb)($^{\circ}$R)	μ, (lb/ft-sec)$\times 10^7$	k, Btu/(sq ft)(hr) ($^{\circ}$F/ft)
A_i	$+3.0211886\times10^{-1}$	$+1.0183520\times10^{2}$	-3.1549916×10^{-2}
B_i	-4.0154230×10^{-4}	-4.4318502×10^{-1}	$+2.7748205\times10^{-4}$
C_i	$+1.0453496\times10^{-6}$	$+2.0278790\times10^{-3}$	-7.9476163×10^{-7}
D_i	-1.4622846×10^{-9}	-3.3304906×10^{-6}	$+1.3507340\times10^{-9}$
E_i	$+1.2215163\times10^{-12}$	$+2.9953491\times10^{-9}$	-1.3400569×10^{-12}
F_i	-5.9444891×10^{-16}	-1.5241633×10^{-12}	$+7.7235024\times10^{-16}$
G_i	$+1.5462398\times10^{-19}$	$+4.1073671\times10^{-16}$	-2.3979968×10^{-19}
H_i	-1.6579048×10^{-23}	-4.5510988×10^{-20}	$+3.1001900\times10^{-23}$

k_f(stainless steel) = 16.3 Btu/(sq ft)(hr)($^{\circ}$F/ft);

k_f(stainless-clad copper) = 108 Btu/(sq ft)(hr)($^{\circ}$F/ft).

(The stainless-clad copper fin conductivity is based on k_f at 2100° R for pure copper of 200 Btu/(sq ft)(hr) ($^{\circ}$F/ft).)

TABLE III. - HEAT-EXCHANGER DESCRIPTION PARAMETERS

Class	Heat-exchanger type	Figure in ref. 2	Core	Performance parameters						Physical parameters						
				Friction factor, f			Heat-transfer parameter, j, eq. (22)			Hydraulic diameter, D_{hy}, ft	S_x/L_xA_3, ft^{-1}	W_x/L_xA_3, lb/ft^3	S_f/S_x	Fin thickness, d, ft	Fin height, l, ft	α
				A_f	B_f	C_f	A_j	B_j	C_j							
I	Round smooth tubes	40	1	0	0.042	-0.2	0	0.021	-0.2	0.01296	310	292	-----	--------	-------	0.3226
	Flattened round tubes	42	2	.00615	700	-1.5	0	.0067	-.09	.01433	280	263	-----	--------	-------	.3226
	Dimpled flat tubes	43	3	.0042	1.5	-.7	0	.044	-.274	.01116	358	323	-----	--------	-------	.3226
II	Staggered tube banks	46	4	0	0.21	-0.2	0	0.23	-0.4	0.01250	320	311	-----	--------	-------	0.200
	In-line tube banks	54	5	0	.08	-.0875	0	.152	-.356	.01237	324	311	-----	--------	-------	.200
	Flattened tube banks	57	6	.019	0	1	.005	0	1	.01433	280	252	-----	--------	-------	.386
	Dimpled flat tube banks	58	7	.0248	0	1	0	.0362	-.2	.0160	250	230	-----	--------	-------	.423
III	Plain plate fin	65	8	0.0078	31.0	-1.1	0.0026	1.24	-0.85	0.00848	472	155	0.844	0.0005	0.0134	0.434
		67	8-1	0	.0558	-.21	0	.0162	-.181	.00615	650	199	.849	.0005	.0100	.412
		60	8-2	0	.0914	-.27	0	.0442	-.268	.02016	198	99	.719	.0005	.0205	.466
		61	8-3	0	.0424	-.19	.00359	-.06853	.69	.0182	220	112	.728	.00083	.0175	.448
		62	8-4	0	.0436	-.19	0	.0114	-.155	.0152	263	97	.888	.00067	.0339	.455
		63	8-5	0	.0437	-.174	0	.028	-.237	.01012	395	160	.756	.0005	.0105	.435
		64	8-6	0	.065	-.232	.007	-.000784	.18	.01153	347	123	.854	.00067	.0197	.440
		66	8-7	0	.0245	-.117	0	.0042	-.036	.00876	456	142	.870	.0005	.0170	.433
	Louvered plate fin	80	9	0	0.27	-0.315	0	0.079	-0.315	0.01012	395	160	0.756	0.0005	0.0105	0.435
		68	9-1	0	.116	-.136	0	.10	-.315	.0146	274	142	.640	.0005	.0119	.447
		69	9-2	0	.208	-.156	0	.158	-.348	.0146	274	142	.640	.0005	.0119	.447
		70	9-3	0	.13	-.159	0	.075	-.28	.0146	274	142	.640	.0005	.0119	.447
		71	9-4	0	.174	-.16	0	.141	-.345	.0146	274	142	.640	.0005	.0119	.447
		72	9-5	0	.116	-.148	0	.119	-.335	.01196	334	151	.705	.0005	.0109	.441
		73	9-6	0	.236	-.215	0	.121	-.329	.01196	334	151	.705	.0005	.0109	.441
		74	9-7	.0225	5.04	-.69	0	.191	-.382	.01012	395	160	.756	.0005	.0105	.435
		75	9-8	0	.394	-.283	0	.106	-.308	.01012	395	160	.756	.0005	.0105	.435
		76	9-9	.0259	1.159	-.54	0	.085	-.278	.01012	395	160	.756	.0005	.0105	.435
		77	9-10	.0153	1.419	-.55	0	.110	-.326	.01012	395	160	.756	.0005	.0105	.435
		78	9-11	.0201	5.19	-.76	0	.142	-.354	.01012	395	160	.756	.0005	.0105	.435
		79	9-12	0	.149	-.213	0	.074	-.288	.01012	395	160	.756	.0005	.0105	.435
		81	9-13	.0111	2.37	-.68	0	.061	-.286	.01012	395	160	.756	.0005	.0105	.435
	Strip-fin plate fin	82	10	0.0162	27.5	-1.0	0	0.122	-0.350	0.01012	395	160	0.756	0.0005	0.0105	0.435
		83	10-1	.027	3.70	-.62	0	.0722	-.246	.0112	357	107	.862	.00033	.0196	.460
		84	10-2	.0373	1.49	-.56	-.00058	.104	-.280	.00868	461	143	.873	.0005	.0166	.437
	Wavy-fin plate fin	86	11	0	1.13	-0.43	0	0.215	-0.405	0.00696	575	159	0.892	0.0005	0.0165	0.430
		85	11-1	0	1.18	-.388	0	.201	-.371	.0106	377	127	.847	.0005	.0165	.458
IV	Pin-fin plate fin	90	12	0.153	0	1	0	0.53	-0.413	0.0186	215	214	0.704	0.0027	0.0202	0.326
	Finned round tubes	94	13	.0268	2.08	-.65	.0037	.925	-.65	.01452	276	165	.876	.0158	.0184	.494
	Finned flat tubes	106	14	0	0.285	-0.30	0	0.0915	-0.33	0.01152	347	87	0.845	0.00033	0.01875	0.780
		103	14-1	.0084	4.9	-.75	.00181	.52	-.60	.0138	290	81.4	.813	.00033	.01875	.788
		105	14-2	0	.257	-.274	0	.062	-.27	.01352	296	81.8	.814	.00033	.01875	.788
		102	14-3	.0098	56.78	-1.21	0	.017	-.182	.0118	339	95.8	.795	.00033	.0132	.697
		104	14-4	0	.098	-.183	0	.046	-.267	.0118	339	95.8	.795	.00033	.0132	.697
	Round-tube plate fin	100	15	0	0.1242	-0.209	0	0.1885	-0.415	0.01192	336	140	0.839	0.001084	0.0778	0.534
		101	15-1	0	.1002	-.23	0	.102	-.357	.01268	315	160	.905	.00133	.1354	.497
	Round smooth tubes with wire turbulators	---	1-2	0	0.21	-0.20	0	0.0315	-0.2	Same as core 1						
		---	1-6	0	.42	-.20	0	.042	-.2							
		---	1-100	0	.063	-.20	0	.0252	-.2							

TABLE IV. - $(F_n/W_{EH})_{max}$ FOR ALL EXCHANGERS, SHOWING SOME EFFECTS OF STAINLESS-CLAD COPPER EXTENDED SURFACES

[M_0 = 2.0, z = 60,000 ft, P_2/P_1 = 7, T_w = 2100° R.] 4537

Core	$(F_n/W_{EH})_{max}$		Core	$(F_n/W_{EH})_{max}$	
	k_f = 16.3	k_f = 108		k_f = 16.3	k_f = 108
1	[a]0.497	0.497	9-8	0.581	0.625
2	.480	-----	9-9	[b].584	.627
3	.515	-----	9-10	.571	----
4	0.515	-----	9-11	.572	----
5	.515	-----	9-12	.566	----
6	.530	-----	9-13	.548	----
7	.525	-----	10	.562	----
8	0.530	-----	10-1	.546	----
8-1	[b].568	0.611	10-2	[b].572	.639
8-2	.477	-----	11	[b].573	.644
8-3	.480	-----	11-1	.559	----
8-4	.415	-----	12	0.483	0.522
8-5	.531	-----	13	.498	.554
8-6	.490	-----	14	.534	.610
8-7	.511	-----	14-1	.521	.585
9	.552	-----	14-2	.543	.610
9-1	.525	-----	14-3	.538	----
9-2	.533	-----	14-4	.540	----
9-3	.530	-----	15	.407	.470
9-4	.529	-----	15-1	.309	----
9-5	.547	-----	[c]1-2	0.488	----
9-6	.555	-----	[c]1-6	.512	----
9-7	.572	-----	[c]1-100	.510	----

[a]Reference shell-and-tube core.
[b]Best four cores.
[c]Wire turbulators in smooth tube, ref. 9.

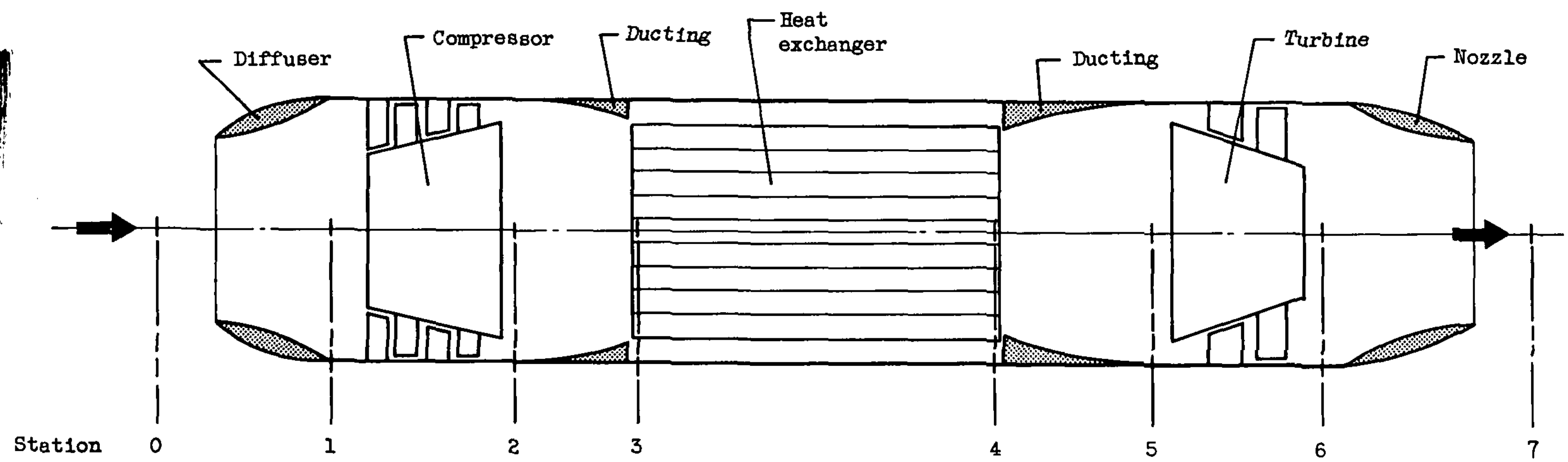

Figure 1. - Basic engine cycle.

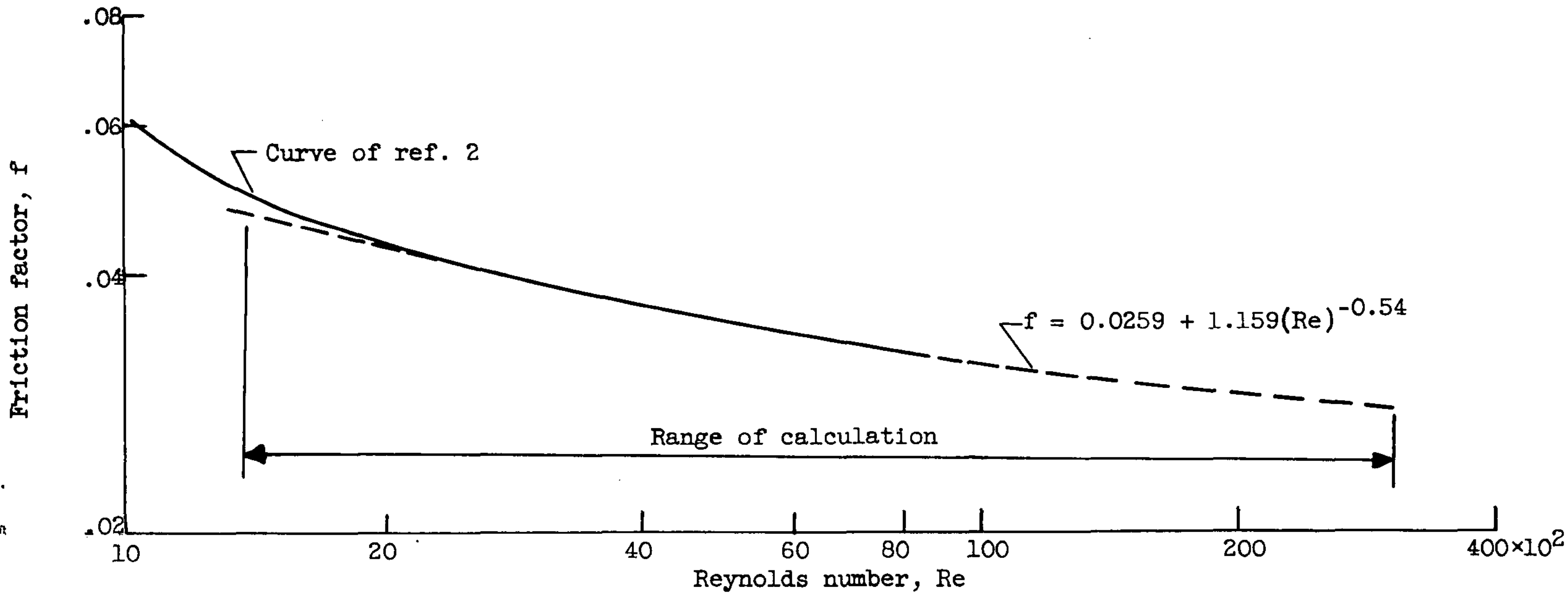

Figure 2. - Typical heat-exchanger (core 9-9) performance curve showing extent of extrapolation.

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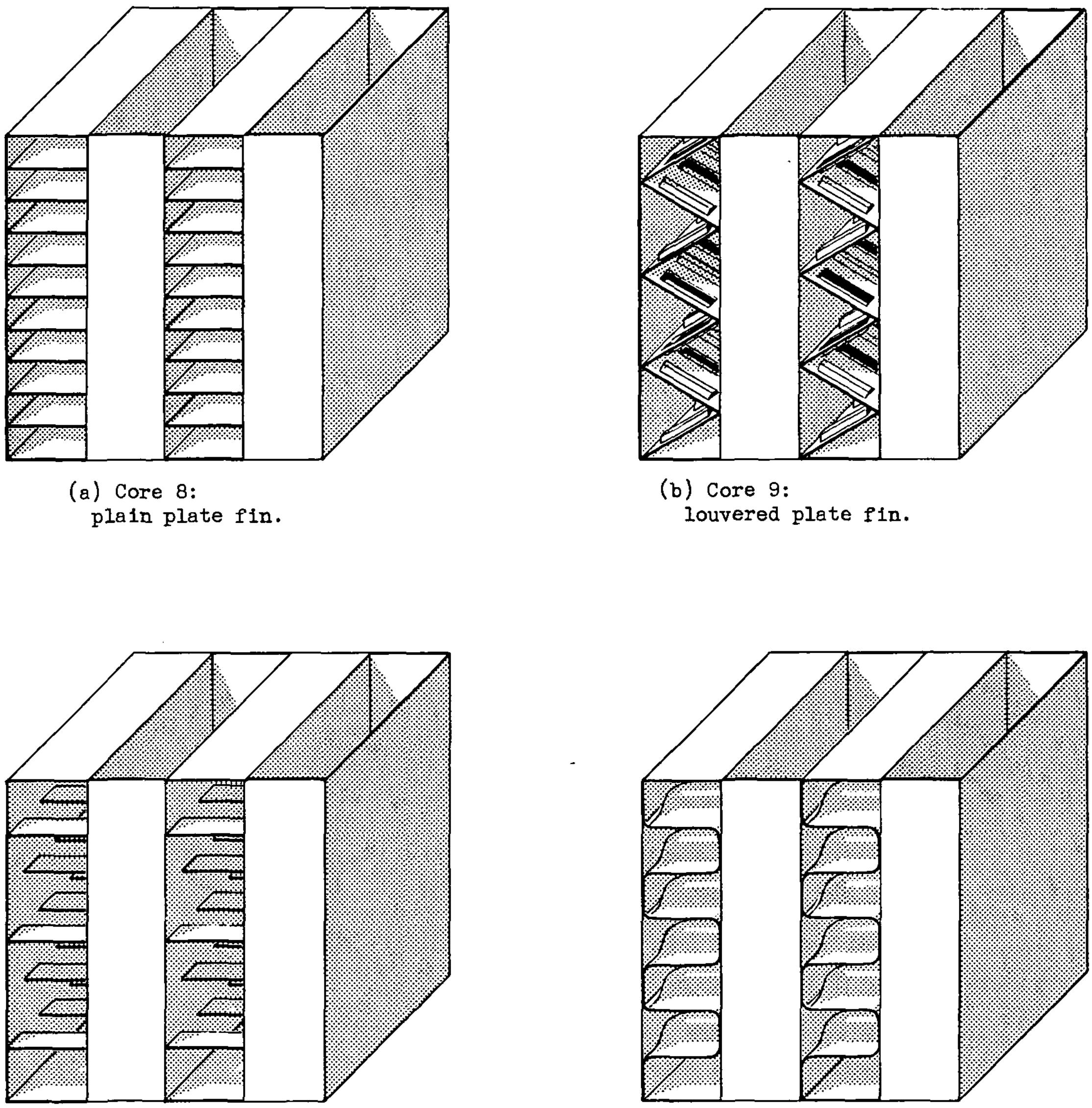

(a) Core 8: plain plate fin.

(b) Core 9: louvered plate fin.

(c) Core 10: strip-fin plate fin.

(d) Core 11: wavy-fin plate fin.

Figure 3. - Core configurations; best four exchanger types (table IV).

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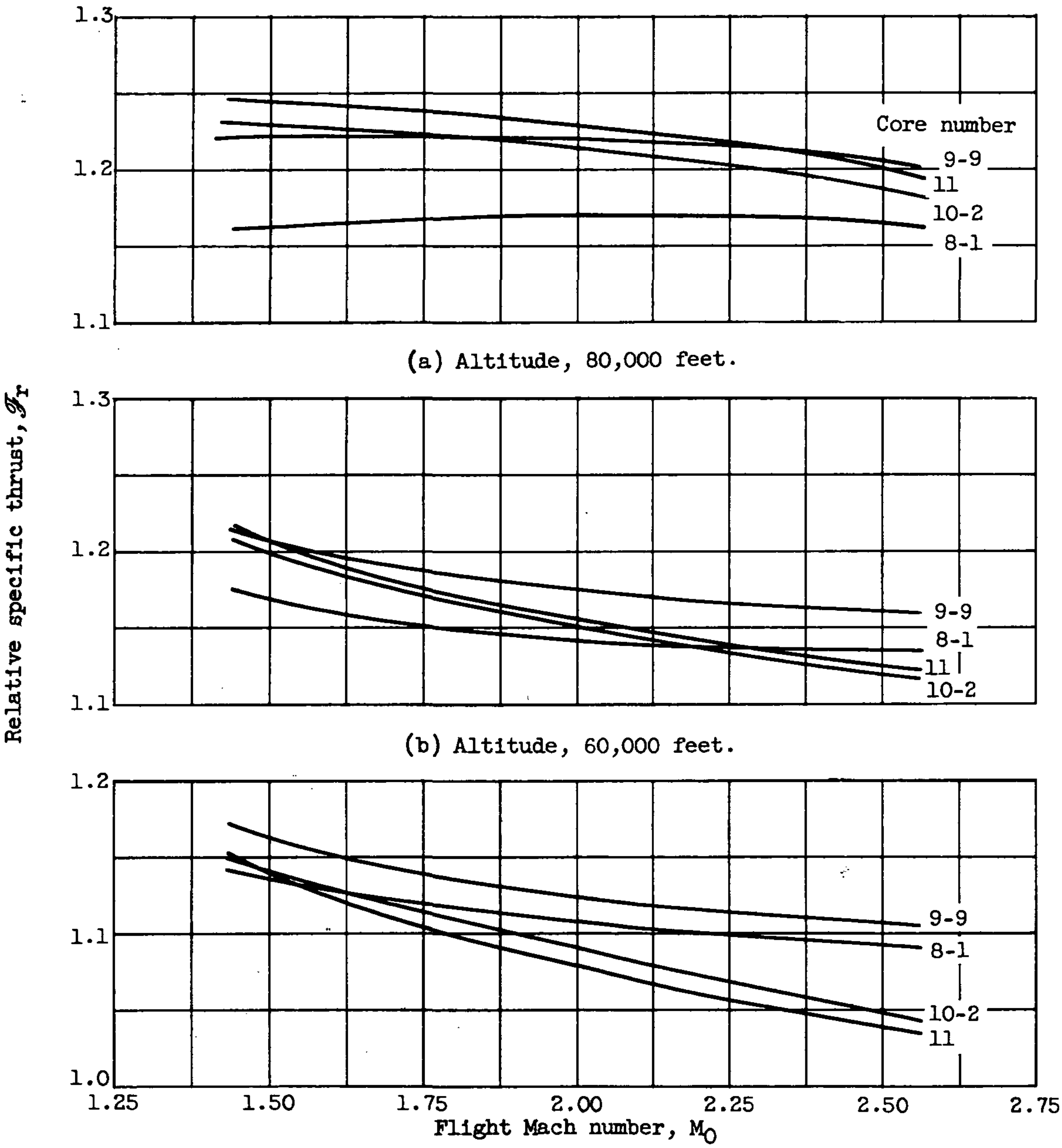

(c) Altitude, 45,000 feet.

Figure 4. - Effect of flight Mach number on relative specific thrust. Wall temperature, 2100° R; compressor total-pressure ratio, 7.

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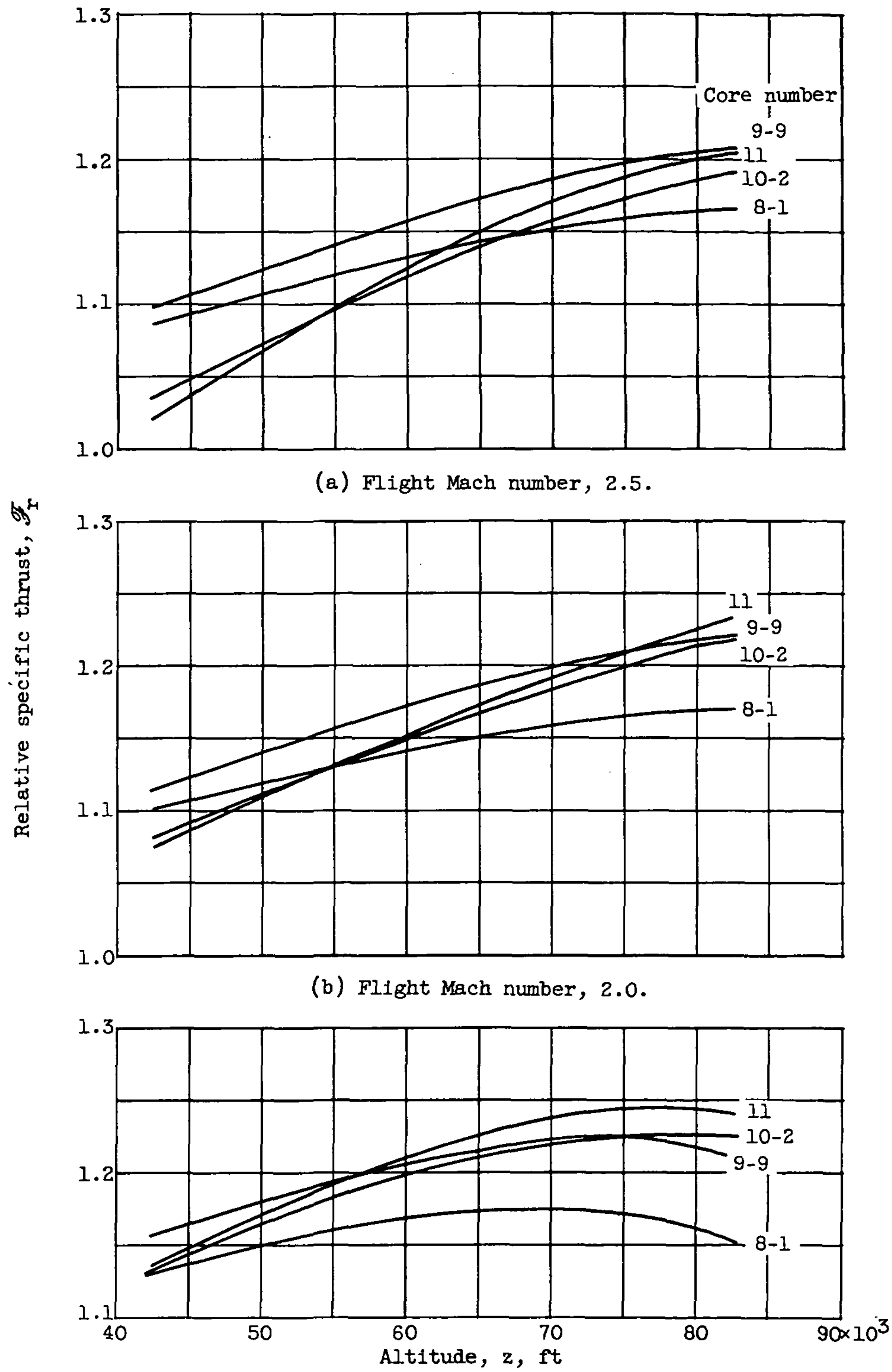

(a) Flight Mach number, 2.5.

(b) Flight Mach number, 2.0.

(c) Flight Mach number, 1.5.

Figure 5. - Effect of altitude on relative specific thrust. Wall temperature, 2100° R; compressor total-pressure ratio, 7.

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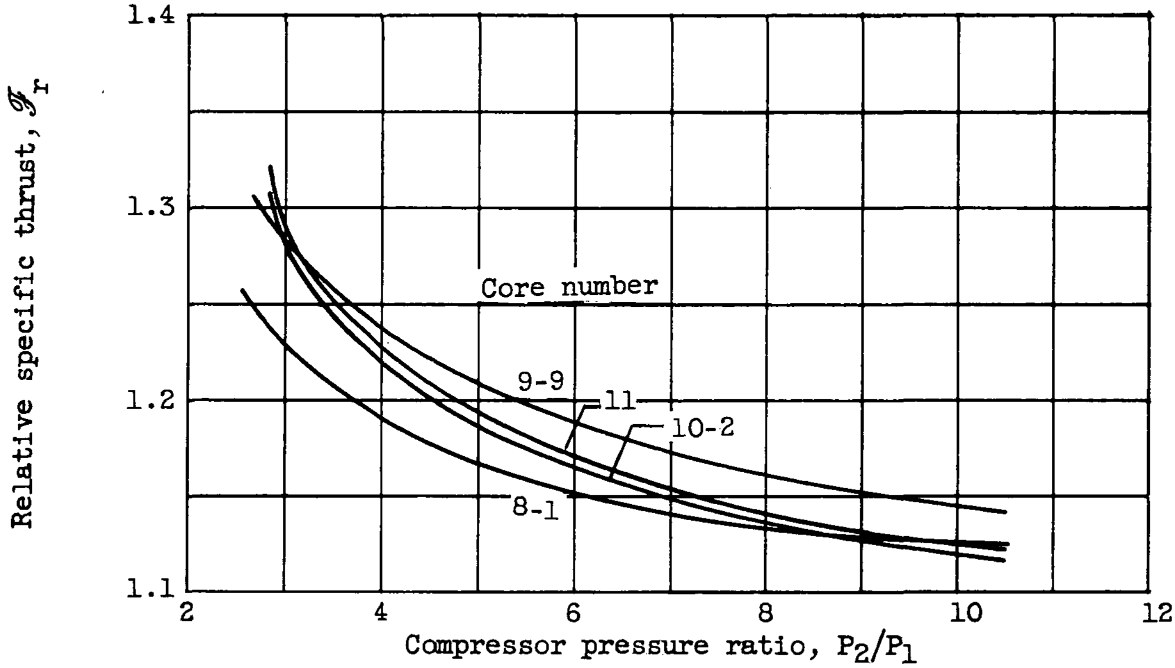

Figure 6. - Effect of compressor pressure ratio on relative specific thrust. Wall temperature, 2100° R; altitude, 60,000 feet; flight Mach number, 2.0.

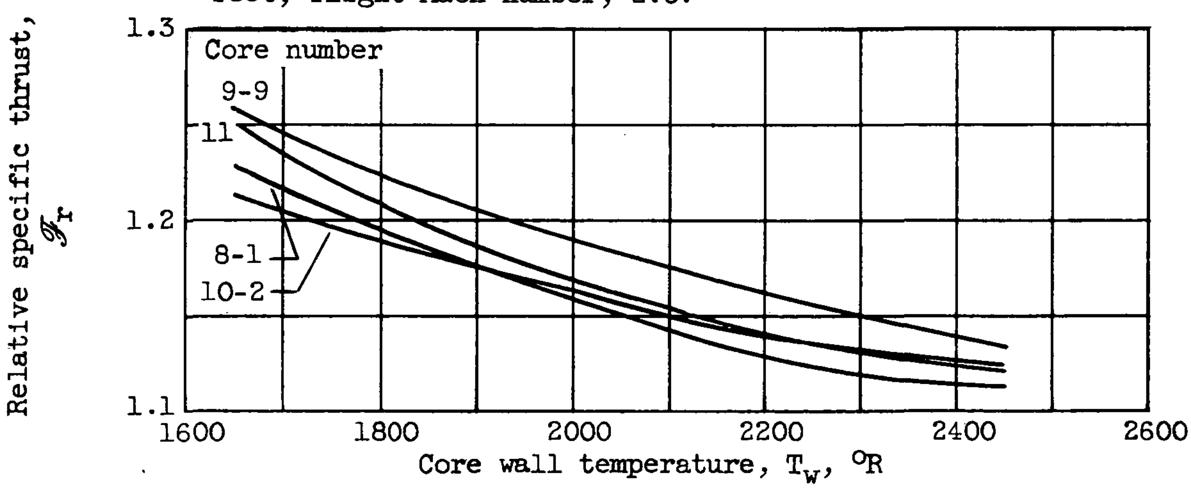

Figure 7. - Effect of core wall temperature on relative specific thrust. Compressor pressure ratio, 7; altitude, 60,000 feet; flight Mach number, 2.0.

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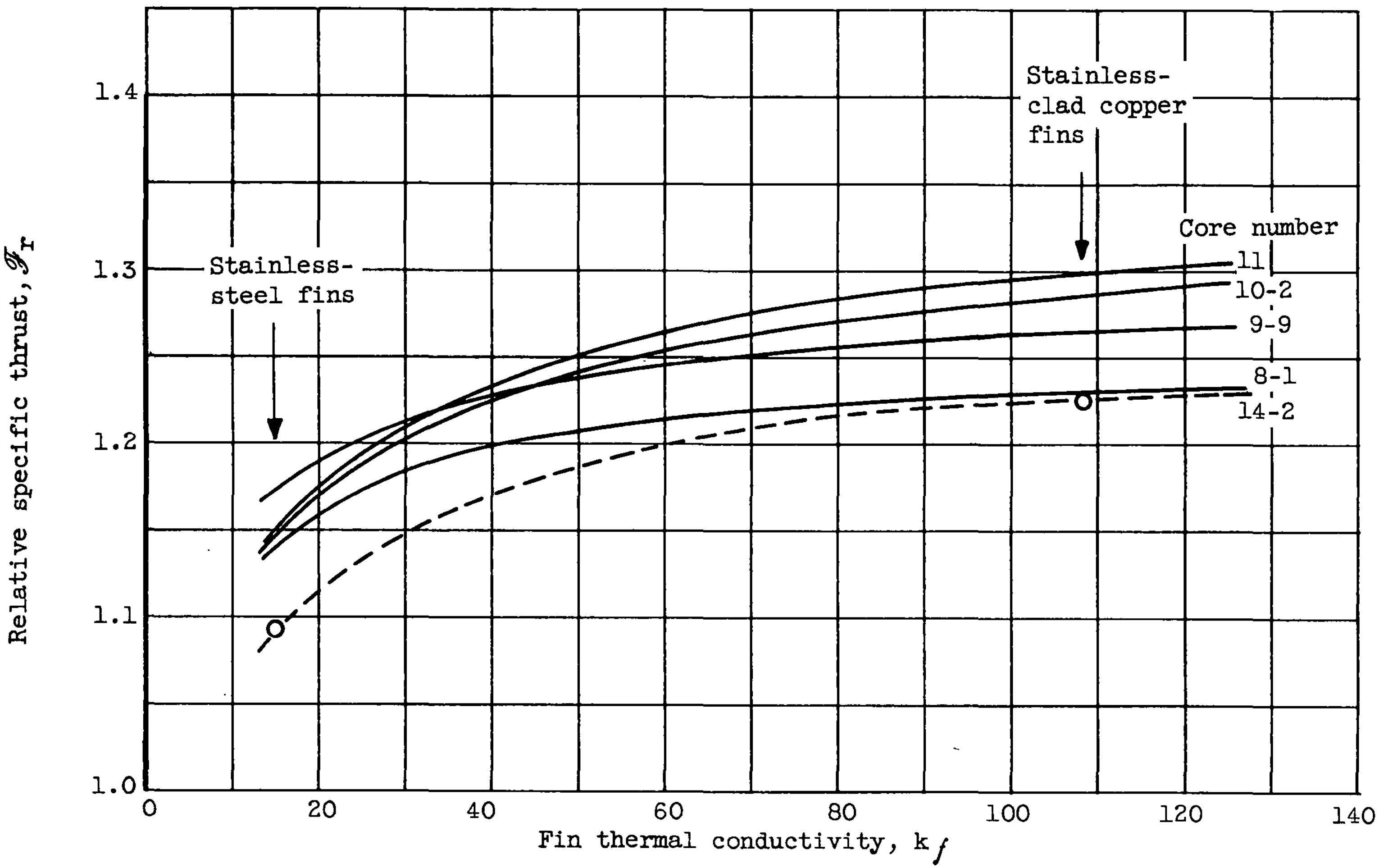

Figure 8. - Effect of fin thermal conductivity on relative specific thrust for four best cores and core 14-2. Wall temperature, 2100° R; compressor total-pressure ratio, 7; altitude, 60,000 feet; flight Mach number, 2.0.

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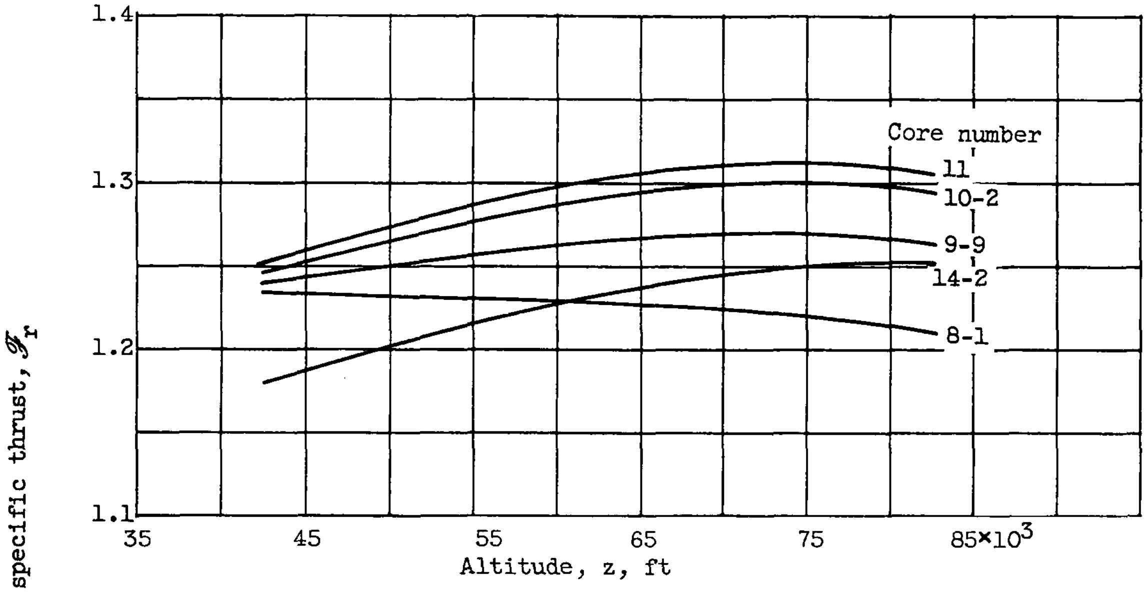
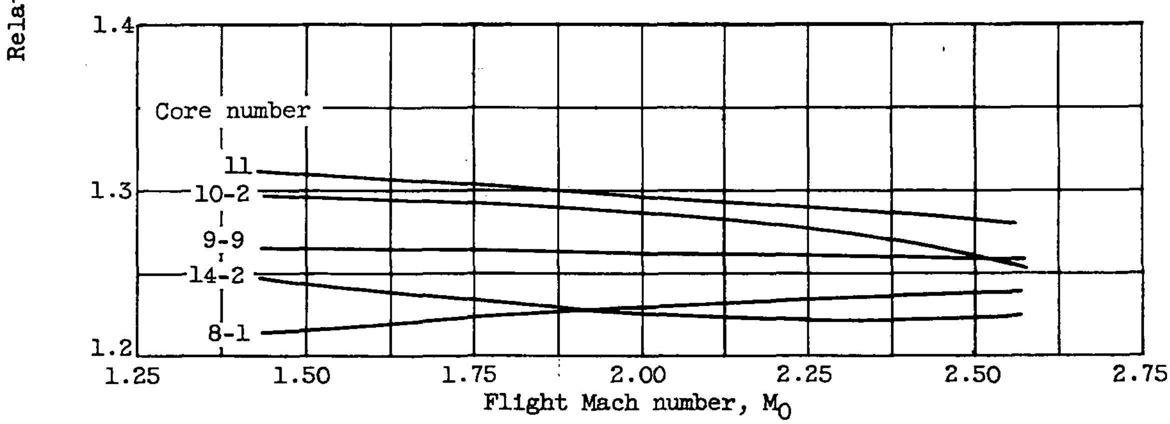


(a) Effect of altitude. Flight Mach number, 2.0.



(b) Effect of flight Mach number. Altitude, 60,000 feet.

Figure 9. - Effect of altitude and flight Mach number on relative specific thrust for fin thermal conductivity of 108. Wall temperature, 2100° R; compressor total-pressure ratio, 7.

[redacted]

[redacted]